BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D.C. 20024

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SUBJECT: Apollo Spacecraft Dynamic Response to SIC Thrust Oscillations and Corresponding Capability, AS-503 and AS-504 Missions - Case 320

DATE: November 26, 1968

FROM: R. E. Hunter

ABSTRACT

The dynamic behavior of the Apollo Spacecraft during Saturn V first stage boost has been a prime concern since the POGO phenomenon occurred during this phase of the flight of Apollo 6 (AS-502). Major programs involving analysis and test of actual Apollo hardware began after the Apollo 6 flight in order to learn as much as possible about the dynamic response and corresponding capability of the Saturn/Apollo Space Vehicle, particularly in a "POGO type environment."

Three dimensional, coupled, finite element (spring - mass) analytical models of the Saturn/Apollo vehicle were developed by MSC and compared to vibration tests of actual flight hardware. Comparisons between analysis and test revealed general agreement, but major discrepancies occurred in the LM lateral response frequency and in the amplitude of SPS tank lateral response.

Correction of the LM discrepancy could significantly change overall analytical spacecraft response. It is recommended that this be investigated prior to the AS-504 flight. The excessive amplitude of SPS tank analytical response makes results conservative, but the capability of the SPS tanks, the critical components for the AS-503 C-Prime mission, is great enough to survive the expected environment (based on the use of accumulators to suppress POGO).

It is shown that there is no known reason to suspect the capabilities of the Apollo hardware to survive the AS-503 C-Prime mission (Apollo 8) based on a successful suppression of the POGO phenomenon. Several remaining concerns relating primarily to the AS-504 (Apollo 9) mission are discussed and the following additional work, some of which is already in progress, is suggested:

1. The analytical test discrepancies now present in the LM model should be resolved and the corresponding changes in the spacecraft responses should be evaluated prior to the flight of AS-504. This appears to be the only major change that could significantly increase the analytical longitudinal-lateral coupling of the AS-504 vehicle to levels comparable to those experienced on AS-501 and As-502.

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2. MSC should continue to investigate the effects of spacecraft component damping greater than 1% on the dynamic response of the vehicle. This will allow some of the conservatism in the present analysis to be removed.

3. The same analytical procedures used to predict the response of AS-503 and AS-504 should be used to predict the response of AS-501 and/or AS-502. This response can then be compared to the actual in-flight response of the vehicle to determine the capability of the 3-D model to reasonably predict the actual in-flight response of the vehicle. This comparison could also take advantage of the extensive spectral analysis(3) performed on the AS-501 and AS-502 flight data.

4. A complete comparison of the AS-503 C-Prime dynamic in-flight environment with analytical results will also be helpful in refining the analytical predictions of the AS-504 mission.

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MEMORANDUM FOR FILE

INTRODUCTION

As a result of the "POGO environment" experienced on Apollo 6 (AS-502) an agressive program began at MSC to learn as much as possible about the dynamic behavior and corresponding capability of the Saturn/Apollo Space Vehicle. This required both accelerated development of new analytical models and extensive testing of actual flight hardware.

Flight results from Apollo 4 and Apollo 6 indicated that there was significant coupling between longitudinal and lateral dynamics. This resulted in the development of a 3-D dynamic model of the entire space vehicle; the size and analytical detail of this model represents an industry first in dynamic analysis of structures.

The realization that analytical results alone would be insufficient to establish the necessary confidence in the dynamic capability of the spacecraft structure led to a dynamic test of actual Apollo flight hardware. This test was needed to verify the analytical model of the Apollo Block II hardware. Extensive correlation of analytically predicted Spacecraft response and actual test results revealed both areas of concern and areas of excessive conservatism in the analytical results.

I have attempted in this memorandum to identify the capability of the Apollo Spacecraft to withstand the dynamic boost environment of the Saturn V launch vehicle. It is apparent at this stage that the structural capability of the AS-503 C-Prime mission hardware far exceeds the expected dynamic environment for this mission, but there remain concerns with regard to AS-504, and additional analysis is recommended prior to this flight.

ANALYTICAL EFFORT

Many dynamic math models of the Saturn Apollo vehicle have been generated during the development of the actual hardware. In general these models have considered longitudinal and lateral dynamics separately.

Post Flight analyses of the first two Saturn V flights indicated that there was significant longitudinal-lateral coupling (3: 1 at the CM on 501, 1: 1 at the CM on 502). These flight results and the "POGO environment" encouraged development of a 3-D analytical model that represents the Apollo Saturn structural dynamic behavior, consistent with "state of the art" analytical and computational procedures. This model attempts to represent all known significant coupling in the spacecraft, both static (stiffness coupling) and dynamic (mass coupling). No launch vehicle coupling has been included to date; the significance of the eccentric mass distributions in the launch vehicle is now being evaluated by MSFC.

The model has seven elastic degrees of freedom:

X - longitudinal motion

Y - yaw motion

Z - pitch motion

R_X- rotation about X

R_y- rotation about y

R_z- rotation about z

ΔR- radial motion (perpendicular to X),

and 102 mass points with a total of 287 degrees of freedom (from 1 to 7 for each mass point).

Appendix A gives a more complete description of the model and analytical procedures now being used by Boeing/MSC to calculate normal 3-D modes and frequencies of vibration of the total space vehicle. Not all 287 modes in such a model are of value since the accuracy decreases with increasing mode number. Modal deflections are, in general, less accurate than modal frequencies; both tend to decrease in accuracy with increasing mode number. This trend is apparent in the correlation of analytical and test results.

RESPONSE ANALYSIS

A 3-D model representative of the AS-503 C-Prime space vehicle was used to determine the steady state response of the spacecraft to longitudinal thrust oscillations of the F-1 engines. The thrust oscillation frequency was set equal to the resonant frequency of those low frequency modes that gave significant spacecraft response. Typical results are given in figures 1 through 9. The steady state response of the CM forward bulkhead, SPS oxidizer sump tank, and LTA-B are shown at flight times of 79 sec. (Max. $q\alpha$), 109 sec., and 125 sec. (Center engine cut-off) after liftoff. The amplitude of the F-1 engine thrust oscillation, 15,000 lbs. zero-to-peak, is approximately equivalent to that experienced on Apollo 6 (AS-502). Figures 1 through 9 are analytically accurate at the resonant peaks only; the "band width" of the resonance is only approximately sketched and is quite narrow due to the lightly damped nature of the structure. Based on this analysis, the following observations can be made about a "Pogo" environment on the AS-503 C-Prime mission.

CM RESPONSE

The sensitivity of the CM to thrust oscillations in the first longitudinal mode increases with time from liftoff (0.46 g's zero-to-peak at T = 79 sec. to 0.88 g's at T = 125 sec.). This is due to SIC Stage propellant depletion and a corresponding decrease in vehicle inertia. Longitudinal (X) to lateral $(Y^2 + Z^2)^{1/2}$ coupling appears to be quite small at the lowest major resonant frequency (9:1 at T = 125 sec.). At the higher resonant frequencies the amount of longitudinal to lateral coupling increases with flight time to about 1:1 at T = 125 sec. This is caused primarily by the increased lateral response of the SPS tanks as shown in figures 2, 5, and 8 (LTA-B is symmetric about the X axis and has no analytical coupling in the 3-D math model).

SPS TANK RESPONSE

The response shown in figures 2, 5, and 8 is that of the SPS oxidizer sump tank, which is the most critical of the four tanks. The axial response of the SPS Oxidizer Sump Tank is very similar to the axial response of the CM, however, the lateral response of this tank is much greater ($\sim$ 10:1) than the lateral CM response, due to the SPS tank support structure.

The primary support for the SPS tanks are "skirts" riveted to the SM aft bulkhead; very little support is provided at the forward end. Longitudinal deflections of the SM aft bulkhead thus cause a rotational force at the base of the SPS tanks which, in turn, cause large lateral deflections at the top of the tanks. The tanks and support structure appear to resonate at about 6.5 to 7.0Hz, which corresponds to the second space vehicle longitudinal mode. When the tank resonance is nearly identical with the vehicle longitudinal resonance, large lateral accelerations of the SPS tank occur: from 0.51 g's at T = 109 sec. to 2.56 g's at T = 125 sec. (Figures 5 and 8).

LTA-B RESPONSE

The response of LTA-B is almost directly proportional to the CM response, but about 20 to 25% lower over the frequency range of the analysis. LTA-B is considerably lighter and stiffer than an operational LM, which increases the LTA-B resonant frequency well above that of the first and second longitudinal modes of the space vehicle. This means that the amplification from the LTA-B attach points to the LTA-B c.g. is near unity in this frequency range (This amplification is ~2 on the current analysis of the AS-504 space vehicle with LM-3). LTA-B does not have any analytical longitudinal-lateral coupling; all lateral motion is due to analytical representation of CSM assymmetries.

SHORT STACK DYNAMIC TEST-ANALYTICAL VERIFICATION

The results of the Short Stack Dynamic Test conducted at MSC can be used to obtain a quantitative feel for the validity of the results of the AS-503 C-Prime response analysis. Boeing/Houston has the prime responsibility for analytical reduction of the data obtained in the Short Stack Dynamic Test. The first phase of this effort is complete and documented.[(1)]

The Short Stack Dynamic Test was used to verify the analytical model of the spacecraft; the hardware used in the test consisted of the following items:

Launch Escape System	LES-12
Command Module	CM-20
Service Module	SM-105
Spacecraft Lunar Adapter	SLA10
Instrument Unit	I.U.-211
S-IVB Forward Skirt	500
Lunar Module	LM-2

A sinusoidal longitudinal force was applied at the base of the S-IVB forward skirt and the resulting response of the structure was measured at several hundred locations. The resulting accelerations at the base of the S-IVB forward skirt were then used as a boundary condition to determine the dynamic response of the analytical model. This procedure allowed a direct comparison between the dynamic response of the hardware and the math model.

Comparison of the two results verified the belief that while 1% critical damping is representative of overall space vehicle dynamic response, the damping in the complex structure of the spacecraft is significantly higher. This increase in spacecraft damping makes the amplitude of the AS-503 C-Prime response, as previously discussed and shown in Figures 1 through 9, conservative.

Further refinements in this area will be used to improve the predicted spacecraft response on AS-504 and subsequent vehicles.

The dynamic responses of the short stack hardware and the math model agreed quite well with the exception of two rather major discrepancies. The lowest LM-SLA lateral resonant frequency occurred at 4.5 Hz analytically but at 4.9 Hz in the test, indicating that either the SLA or the LM model needs to be stiffened to produce agreement with the test results. Correcting of this discrepancy could increase longitudinal-lateral coupling in the AS-504 analysis. This will not affect the AS-503 C-Prime analysis due to the use of the LTA-B instead of an operational LM. Analytical results now show longitudinal-lateral coupling on AS-504 significantly below that experienced on AS-501 (3 = 1 at the CM) and AS-502 (1 = 1 at the CM). This difference could be a real vehicle difference due to weight and stiffness changes but the changes in the LM model to make it agree with tests could significantly increase the coupling on the AS-504 vehicle.

The second major discrepancy concerns the magnitude of the SPS tank response. While SPS tank resonant frequencies are accurate, the calculated peak response generally exceeds the measured response, in some cases by a factor of 5 or greater. Since the SPS propellant loading was similar in the short stack test to what it will be in the AS-503 C-Prime mission, there is every reason to believe that the SPS tank analytical response results for this mission are very conservative.

The math model was not considered adequate to make detailed comparisons with test results above about 10 Hz. Significant dynamic shell mode responses of the SLA/IU/S-IVB Forward Skirt begin above 10 Hz, which the math model cannot predict. The number of analytical springs and mass points needed to reasonably describe shell dynamics of the Saturn V would be prohibitive.

AS-503 C-PRIME DYNAMIC CAPABILITY

All indications are that the present AS-503 C-Prime mission dynamic response analysis is a conservative estimate of the peak low frequency accelerations that the spacecraft will experience from F-1 engine thrust oscillations of a given amplitude and frequency.

If we assume that thrust oscillations are equally likely at any longitudinal frequency, then the most critical S/C component is the SPS Oxidizer Sump Tank for thrust oscillations at about 6.75 Hz (Figure 8). The allowable lateral acceleration at the top of the SPS tank for this frequency is given by NR as 0.63 g's with a safety factor of 1.4, which can be achieved by a 6.73 Hz thrust oscillation with a peak amplitude of 3,400 lbs. When all of the previously stated conservatism relating to the actual tank response is taken into account, the 3,400 pound thrust oscillation amplitude is conservative by a factor of at least 2.

The capability of the AS-503 C-Prime Spacecraft Structure in first mode vibrations (4.5 to 5.5 Hz) is much greater than in the 6 to 7 Hz range. It is very likely that the ultimate capability of the S/C measured in terms of CM axial acceleration is considerably in excess of 1.0g in the first longitudinal mode. Apollo 6 survived 0.7g's in the first mode from peak thrust oscillations of about 15,000 pounds with no failures identifiable with the POGO environment.

PREDICTED THRUST OSCILLATIONS AND C-PRIME DYNAMIC ENVIRONMENT

MSFC is totally confident that the Saturn V POGO phenomenon has been eliminated by the addition of accumulators on the 4 outboard LOX lines to the F-1 engines. All indications are that the maximum peak thrust oscillation at any one frequency, in the absence of POGO, will be 1,800 pounds.[2] The maximum response of the S/C to thrust oscillations of this magnitude cannot be shown to be a problem by even the most conservative analysis. Chart 10 gives a summary of the worst accelerations that could occur on AS-503 C-Prime based on this response analysis with a peak thrust oscillation amplitude of 1,800 pounds. Note that this results in a lateral acceleration at the top of the SPS Oxidizer Sump Tank of only 0.33g's compared to a limit capability of 0.63g's. The peak axial acceleration at the CM would be 0.11g's from response in the 4.5 to 5.5 Hz range. MSFC believes that the accumulator fix to eliminate the POGO phenomenon will reduce thrust oscillations in this 4.5 to 5.5 Hz range well below the 1,800 pounds used to obtain these results.

Thus, for the C-Prime mission I am totally confident that the Spacecraft structure can survive the predicted environment as is. However, if, for some reason the POGO phenomenon reoccurs, very little can be said about what will happen for several reasons:

1. Thrust oscillations could continue to increase until a major hardware failure occurs.
2. Nonlinearities in the system could limit POGO amplitudes to acceptable levels.
3. POGO could occur at several frequencies, and the capability of the structure to survive the resulting dynamic environment is very frequency dependent.

AS-504 DYNAMIC ENVIRONMENT

The ability of AS-504 and subsequent Saturn V space vehicles to withstand low frequency thrust oscillations of any significant magnitude is still questionable due to uncertainties in the accuracy of the present analysis.

If the lateral resonant frequency of the LM in the short stack dynamic test configuration found analytically to be 4.5 hz is made to agree with the test resonant frequency of 4.9 hz, the response of the spacecraft could change considerably.

CONCLUSIONS

There is no reason to suspect the structural capability of the AS-503 C-Prime mission in the absence of a "POGO" environment. Any residual thrust oscillations that are less than 2 times MSFC's predicted worst levels are of no structural concern to this mission.

RECOMMENDATIONS FOR FURTHER ANALYSIS

While the dynamic response of AS-503 C-Prime is acceptable there is much that can be done to improve our confidence in the capability of the AS-504 space vehicle that will carry a LM, which is dynamically far more active at low frequencies than the LTA-B. It is recommended that the following areas be pursued during the time remaining prior to the flight of the AS-504 vehicle:

1. The analytical - test discrepancies now present in the LM model should be resolved and the corresponding changes in the spacecraft responses should be evaluated prior to the flight of AS-504.

2. MSC should continue to investigate the effects of spacecraft component damping greater than 1% on the dynamic response of the vehicle. This will allow some of the conservatism in the present analysis to be removed.

3. The same analytical procedures used to predict the response of AS-503 and AS-504 should be used to predict the response of AS-501 and/or AS-502. This response can then be compared to the actual in-flight response of the vehicle to determine the capability of the 3-D model to reasonably predict the actual in-flight response of the vehicle. This comparison could also take advantage of the extensive spectral analysis(3) performed on the AS-501 and AS-502 flight data.

4. A complete comparison of the AS-503 C-Prime dynamic in-flight environment with analytical results will also be helpful in improving the analytical predictions of the AS-504 mission.

R. E. Hunter

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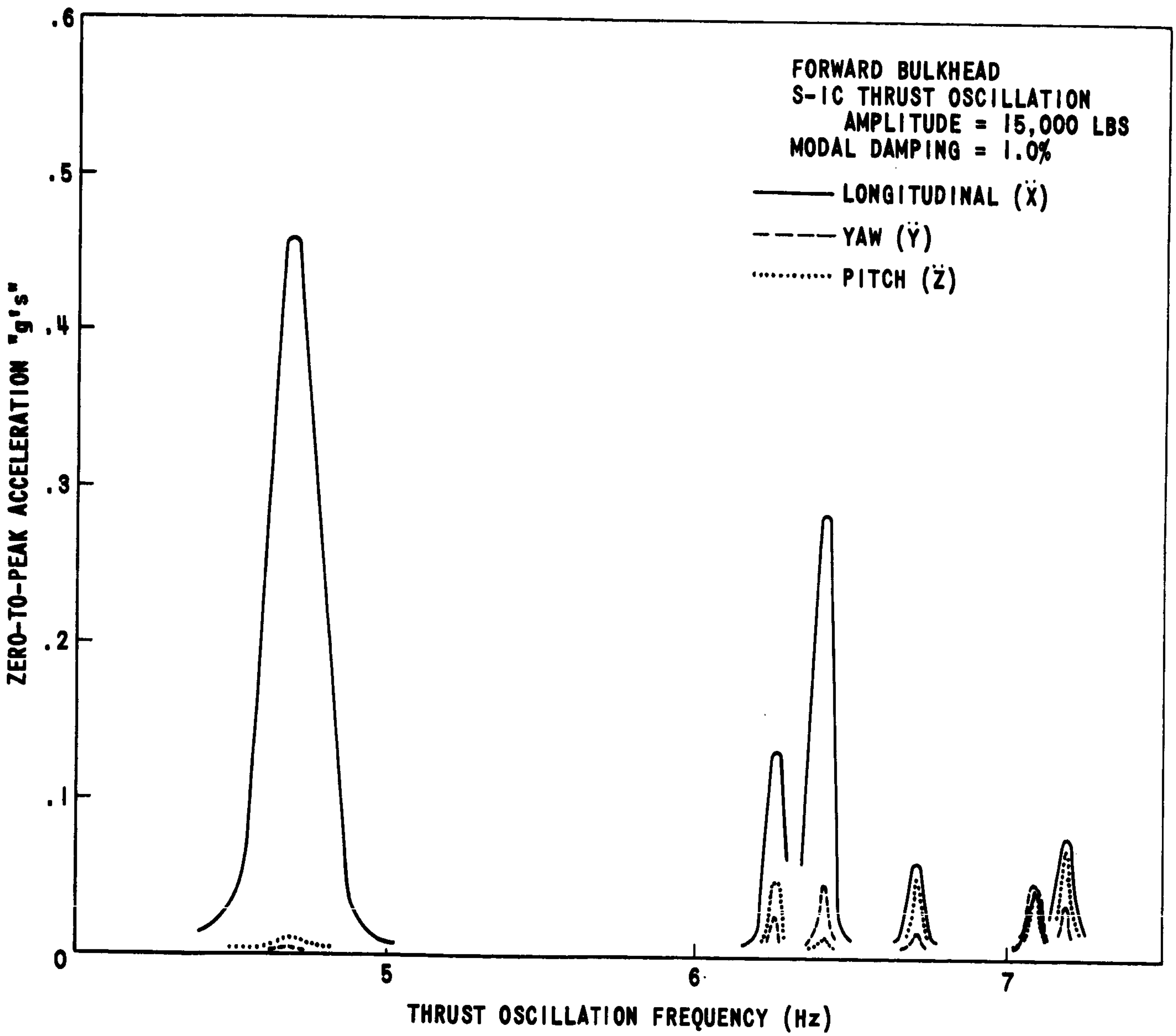

FIGURE 1 AS-503 C' CM RESPONSE TO THRUST OSCILLATION, T = 79 SEC

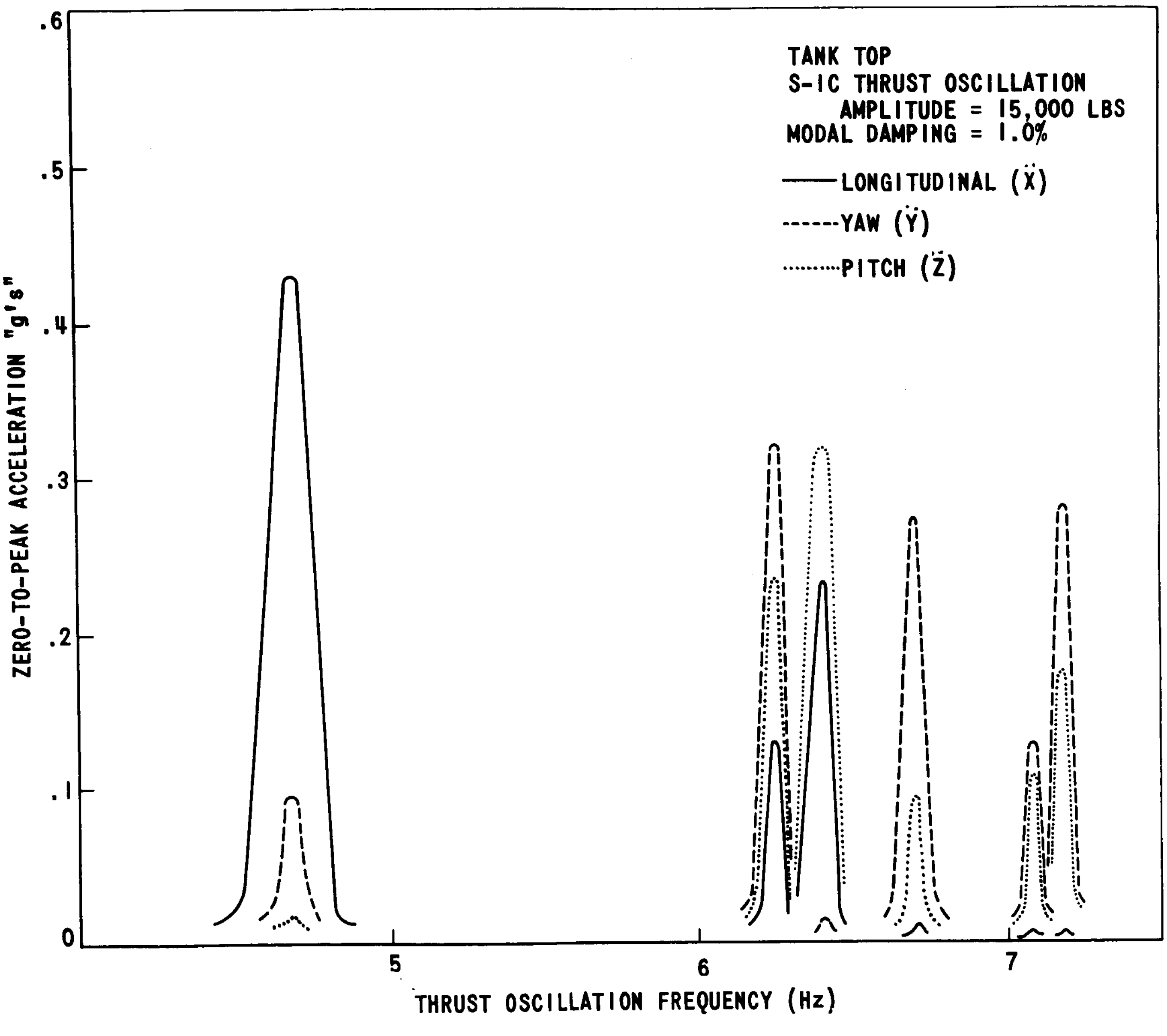

FIGURE 2 AS-503 C' SPS OXIDIZER SUMP TANK RESPONSE TO THRUST OSCILLATION, T = 79 SEC

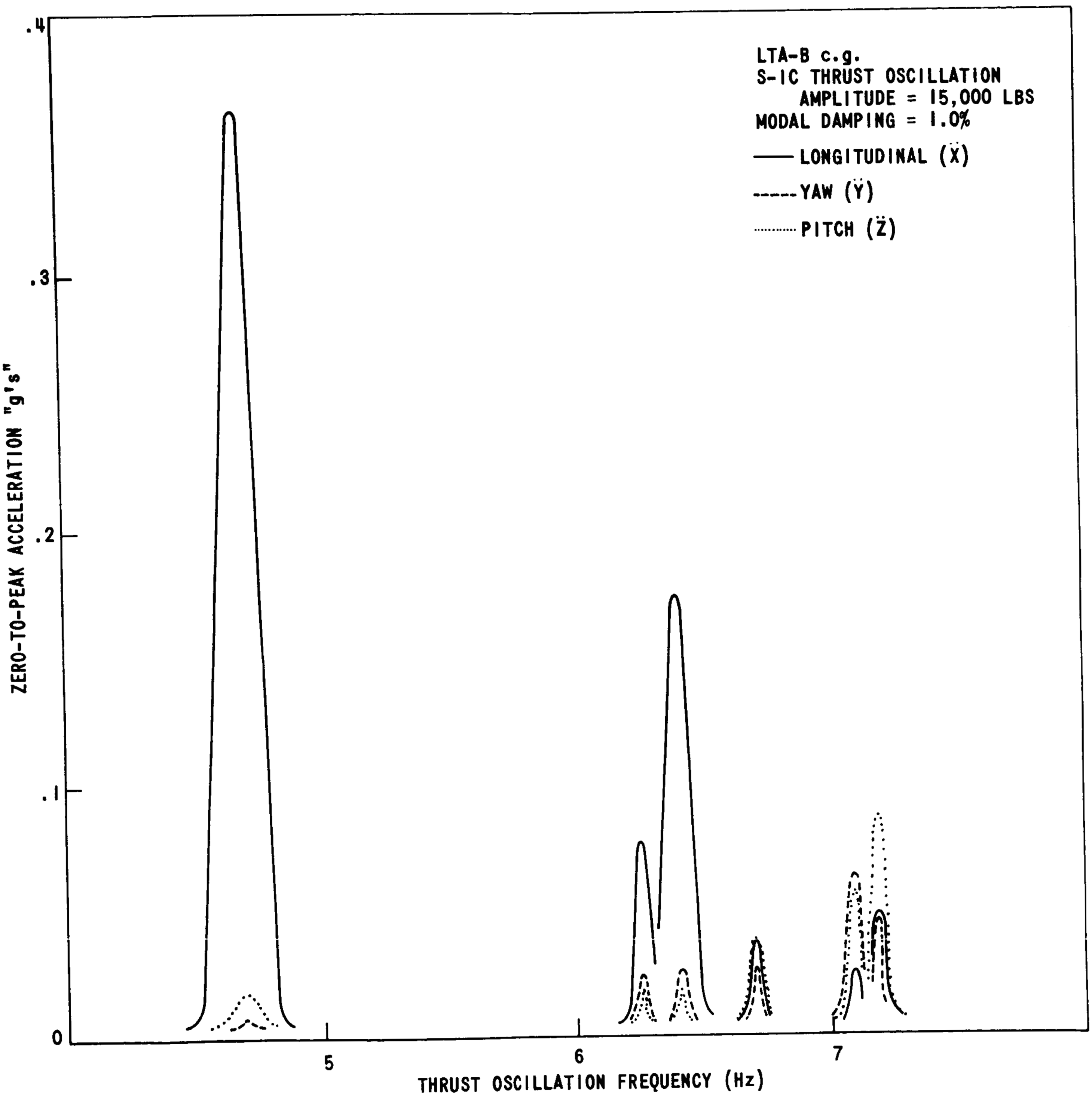

FIGURE 3 AS-503 C' LTA-B RESPONSE TO THRUST OSCILLATION, T = 79 SEC

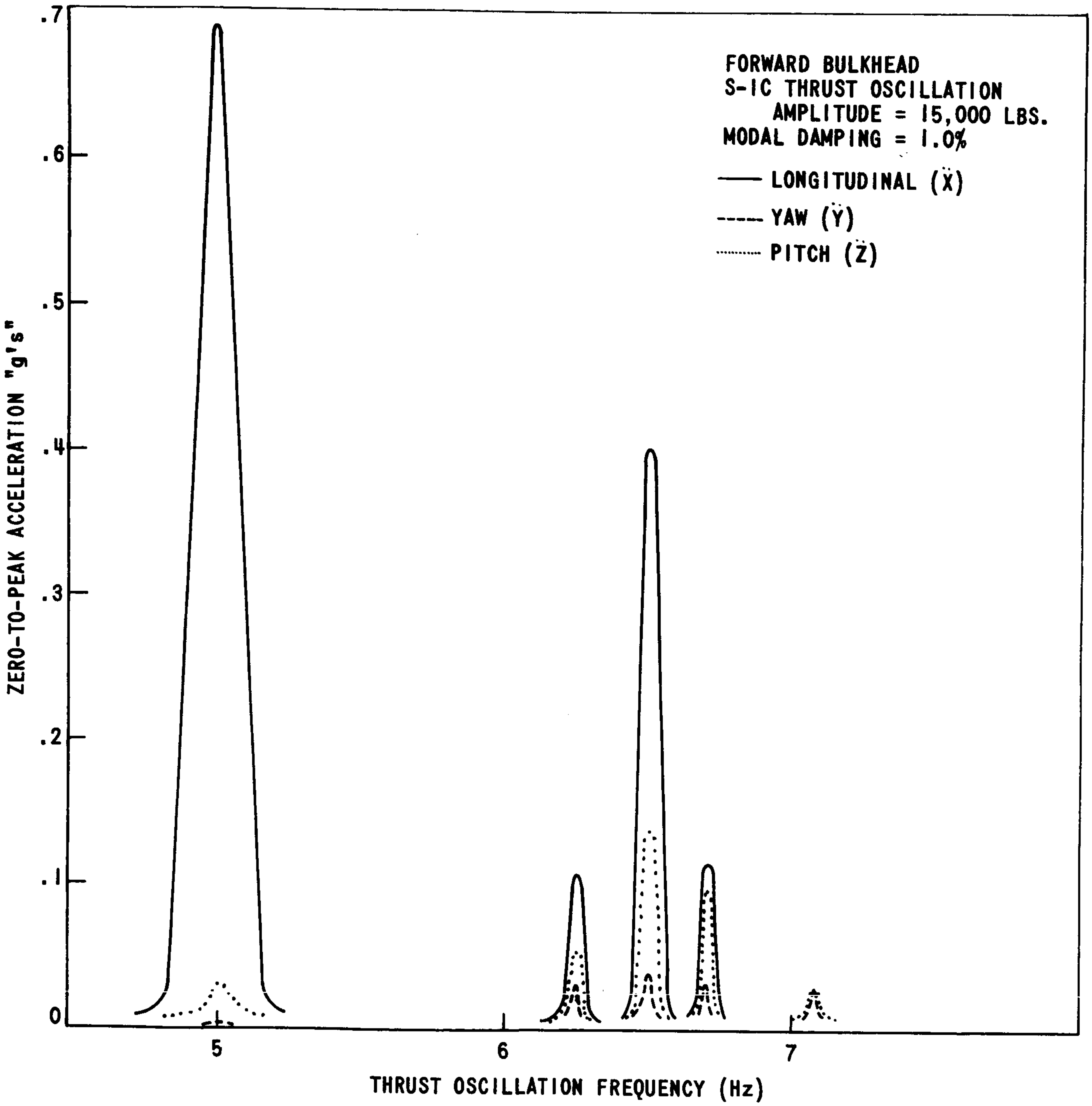

FIGURE 4 AS-503 C' CM RESPONSE TO THRUST OSCILLATION, T = 109 SEC

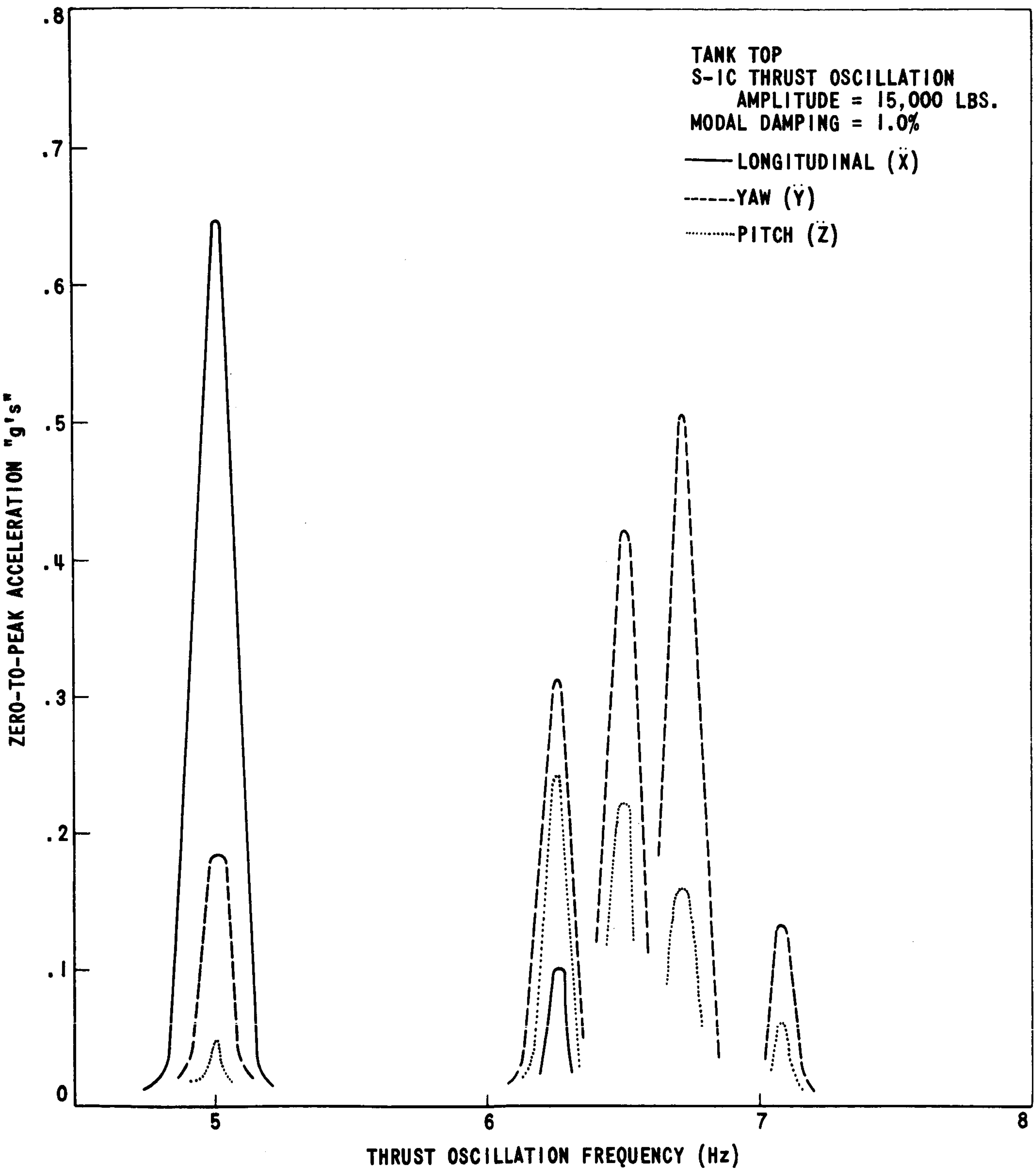

FIGURE 5 AS-503 C' SPS OXIDIZER SUMP TANK RESPONSE TO THRUST OSCILLATION, T = 109 SEC.

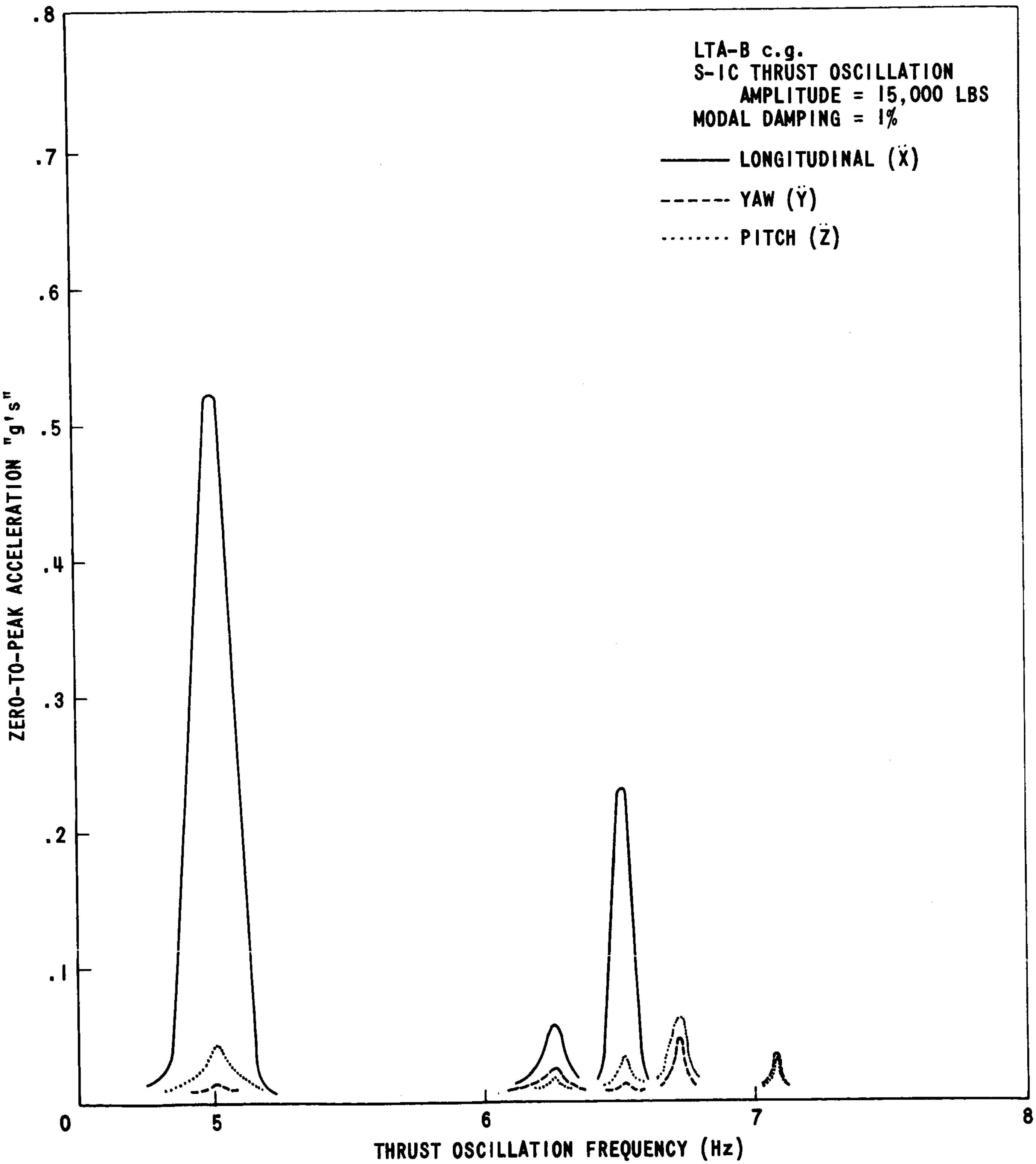

FIGURE 6 AS-503 C' LTA-B RESPONSE TO THRUST OSCILLATION, T = 109 SEC

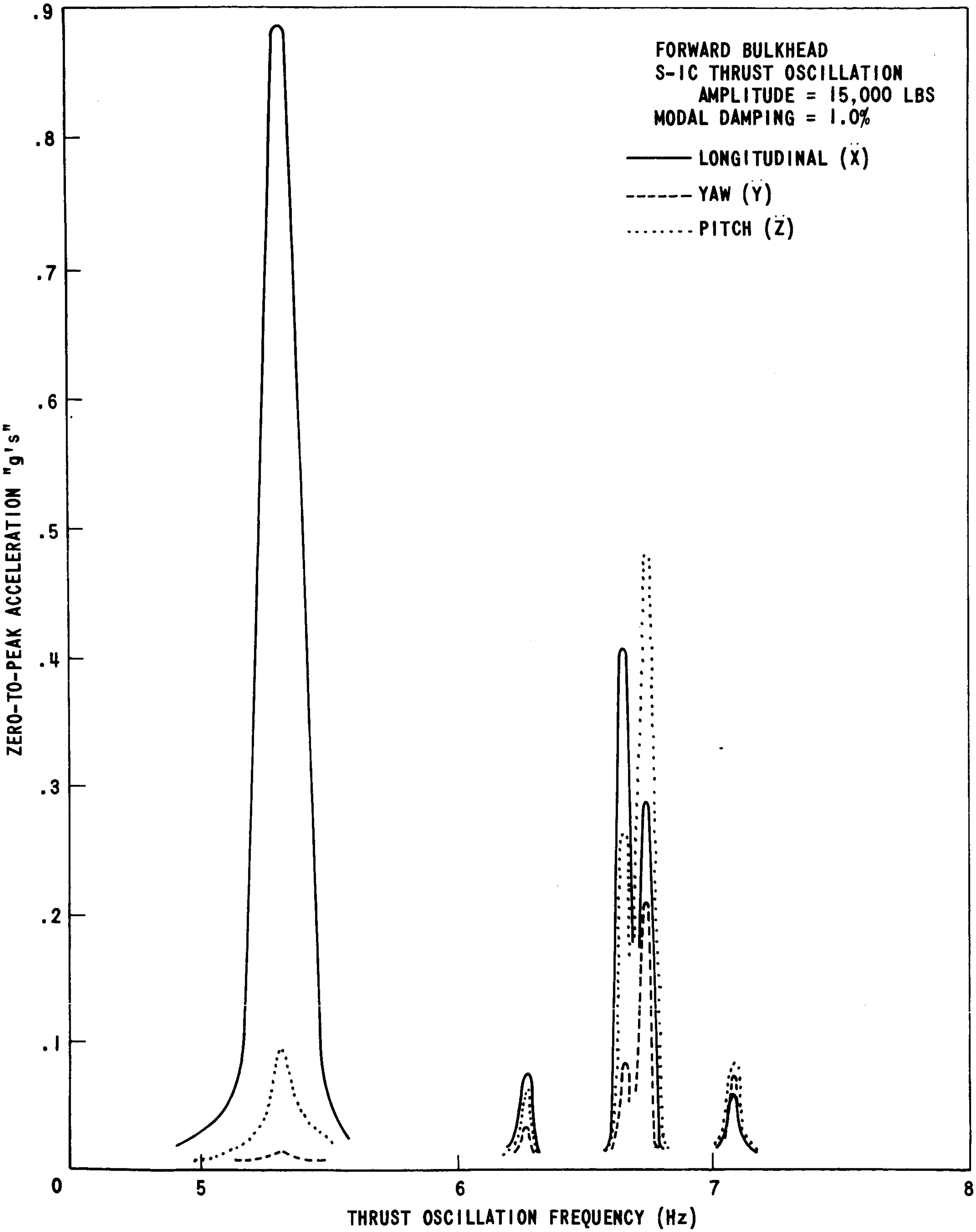

FIGURE 7 AS-503 C' CM RESPONSE TO THRUST OSCILLATION, T = 125 SEC.

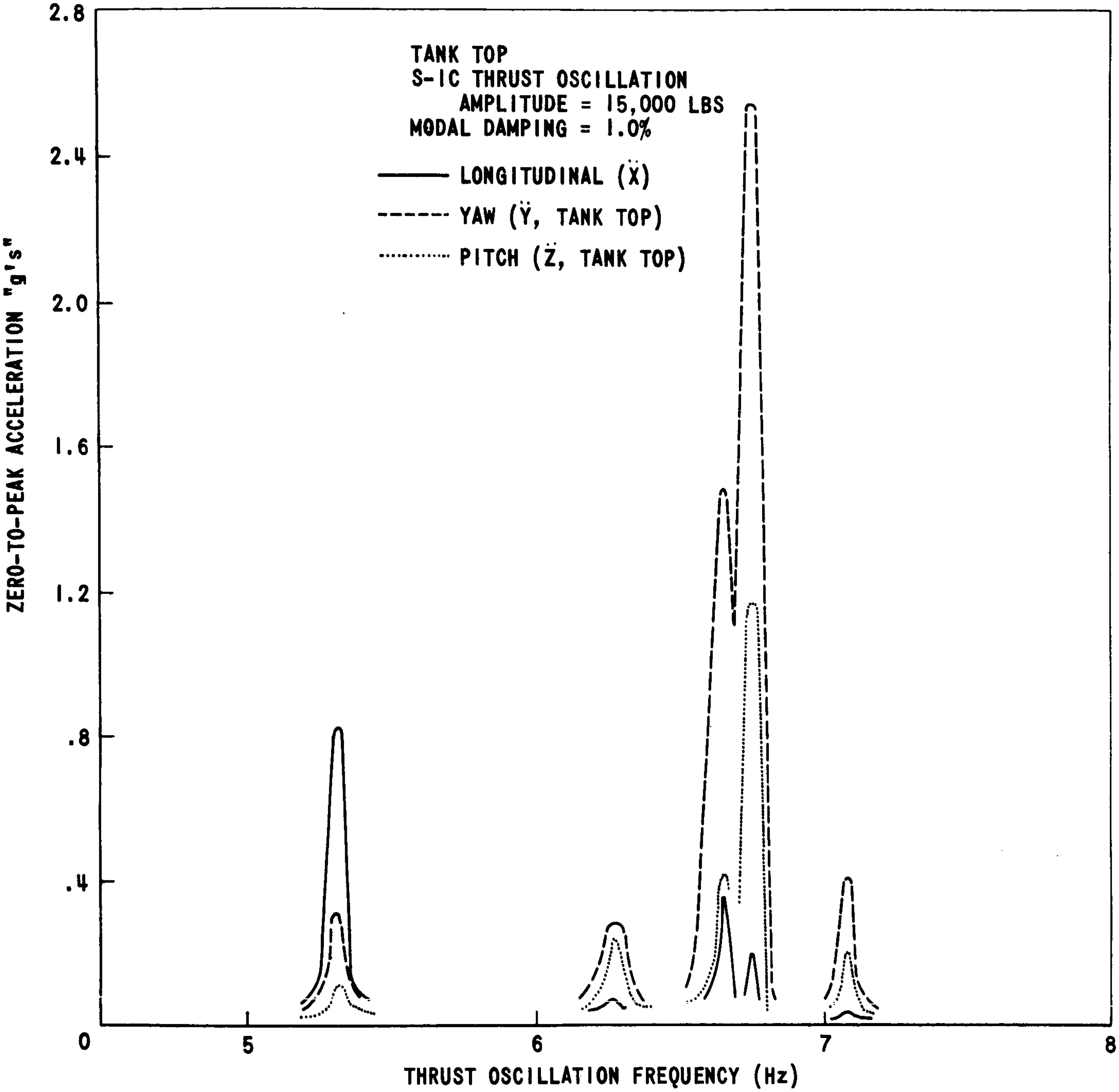

FIGURE 8 AS-503 C' SPS OXIDIZER SUMP TANK RESPONSE TO THRUST OSCILLATION, T = 125 SEC.

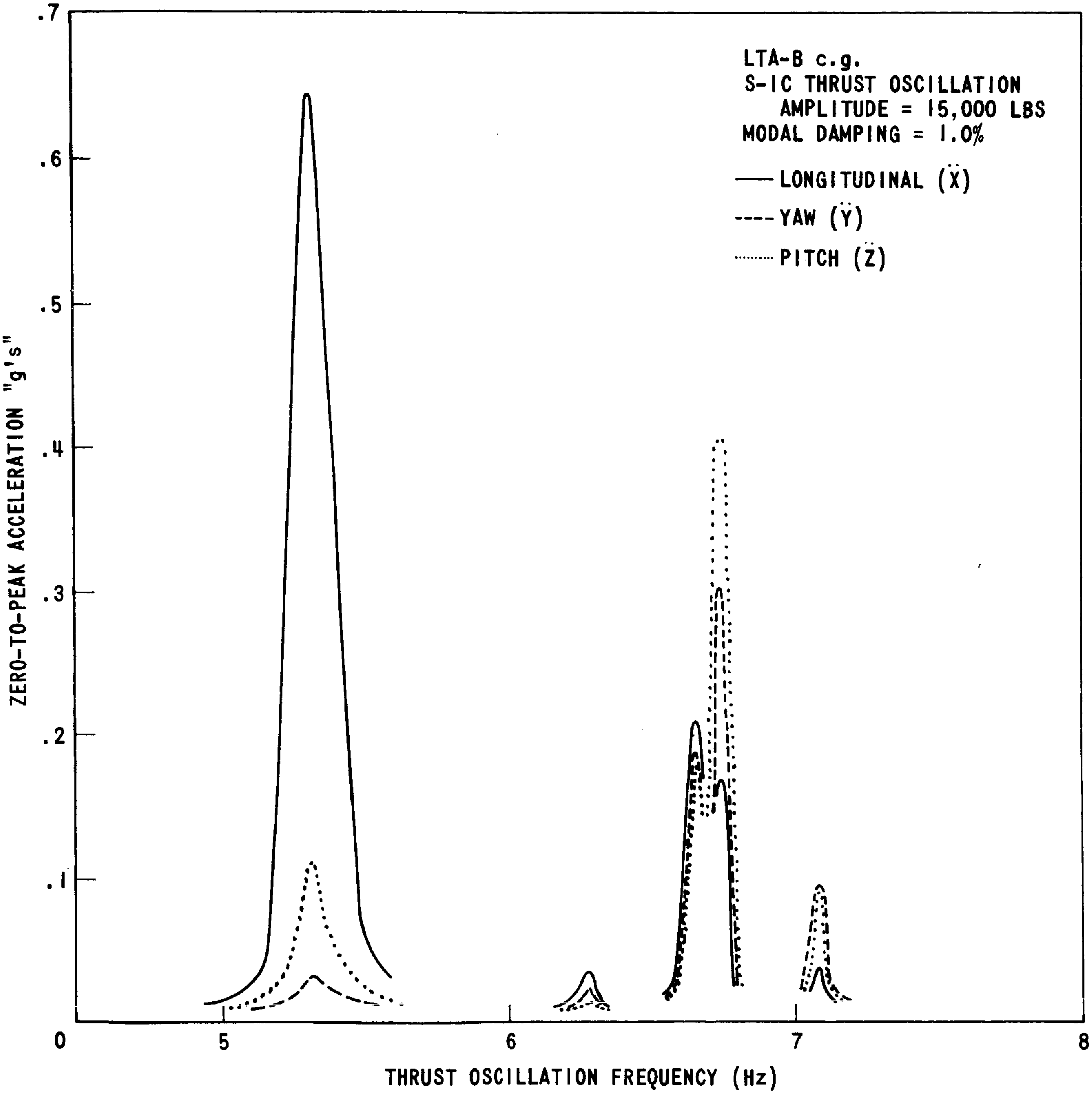

FIGURE 9 AS-503 C' LTA-B RESPONSE TO THRUST OSCILLATION, T = 125 SEC.

COMPONENT		T=79 SEC (MAX $q\alpha$)	T=109 SEC	T=125 SEC (CECO)
COMMAND MODULE LONGITUDINAL ($\ddot{X}$)	FREQUENCY (Hz)	4.69	5.02	5.32
	PEAK ACC. (g's)	.055	.083	.11
SPS OXIDIZER SUMP LATERAL $(\ddot{Y}^2 + \ddot{Z}^2)^{\frac{1}{2}}$	FREQUENCY (Hz)	6.27	6.72	6.76
	PEAK ACC. (g's)	.048	.064	.33
LTA-B LONGITUDINAL ($\ddot{X}$)	FREQUENCY (Hz)	4.69	5.02	5.32
	PEAK ACC. (g's)	.044	.063	.077

FIGURE 10 - EXPECTED AS-503 C-PRIME DYNAMIC ENVIRONMENT
S-IC THRUST OSCILLATION AMPLITUDE = 1,800 LB.

APPENDIX A

The 3-D finite element (spring-mass) math model was prepared by Boeing/Houston from component models received from various sources:

LES	Boeing/Huntsville
CSM	Manned Spacecraft Center
LM	Grumman
SLA/IU/S-IVB Forward Skirt	Boeing/Huntsville
SIC	Boeing/Huntsville
SII	Boeing/Huntsville
SIVB	Boeing/Huntsville

The CSM and LM math models contain all known assymetries that can cause longitudinal-lateral coupling. The launch vehicle coupling is limited to longitudinal-radial motion (tank bulging). While some assymetric mass distributions are known to exist, MSFC does not consider them to be significant. The resulting lumped mass idealization of the "payload" portion of the Apollo/Saturn vehicle is shown in figures 1 through 4. This spring-mass idealization of the structure reduces the analytical response to the solution of ordinary second order, coupled, linear differential equations which appear in matrix notation as:

$$[M]\{\ddot{X}\} + [K]\{X\} = \{F\}$$

M = mass matrix

K = stiffness matrix

F = applied force matrix

X = degrees of freedom

The solution to this problem by modal analysis leads to a standard eigenvalue problem of the form:

$$[K - w_i^2 M] \phi_i = 0$$

W_i = eigenvalue or resonant frequency

ϕ_i = eigenvector or mode shape

The eigenvectors can then be used to perform a coordinate transformation that allows the response of each mode to a particular force to be caluclated separately. The total response of the structure is then the total sum of the response of each mode.

Damping cannot be handled in an analytically straight forward manner using this type of analysis. However, as long as damping is a small percentage of critical damping in each mode, the use of modal damping is the accepted practice. Further discussions on this analytical procedure can be found in any text on analytical dynamics.*

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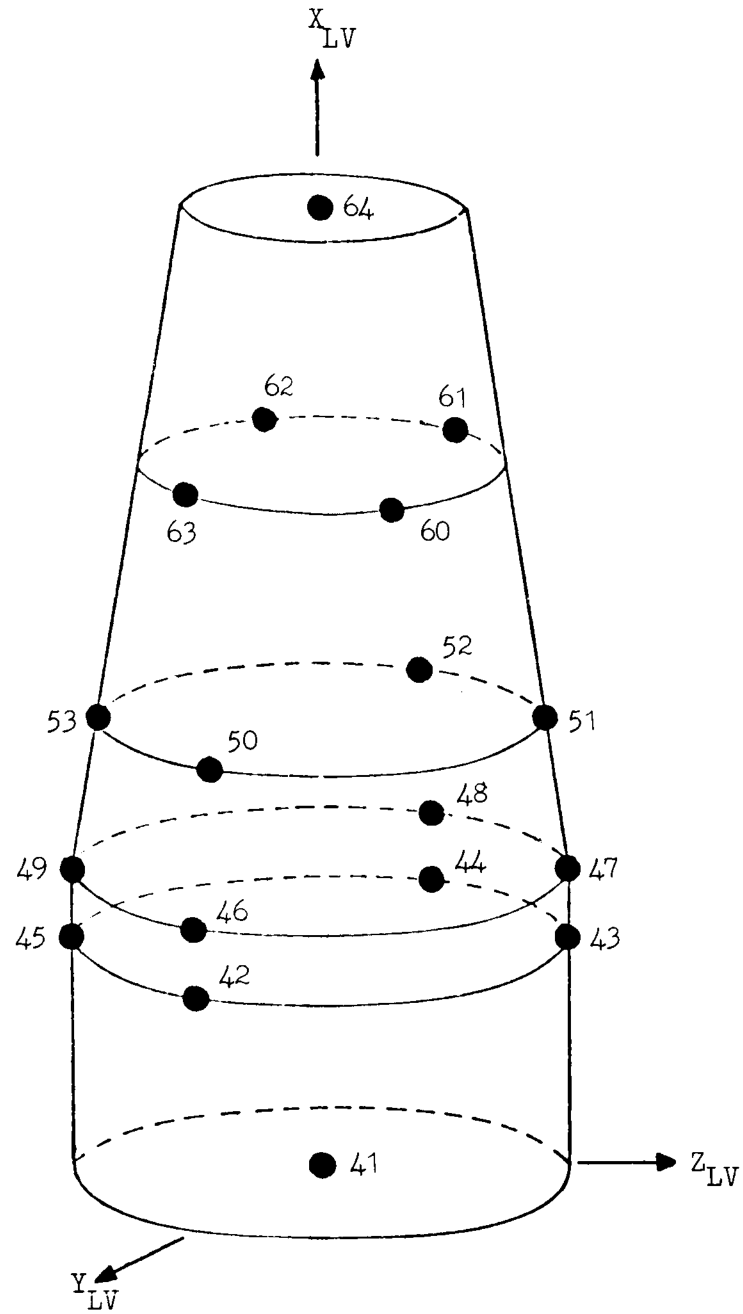
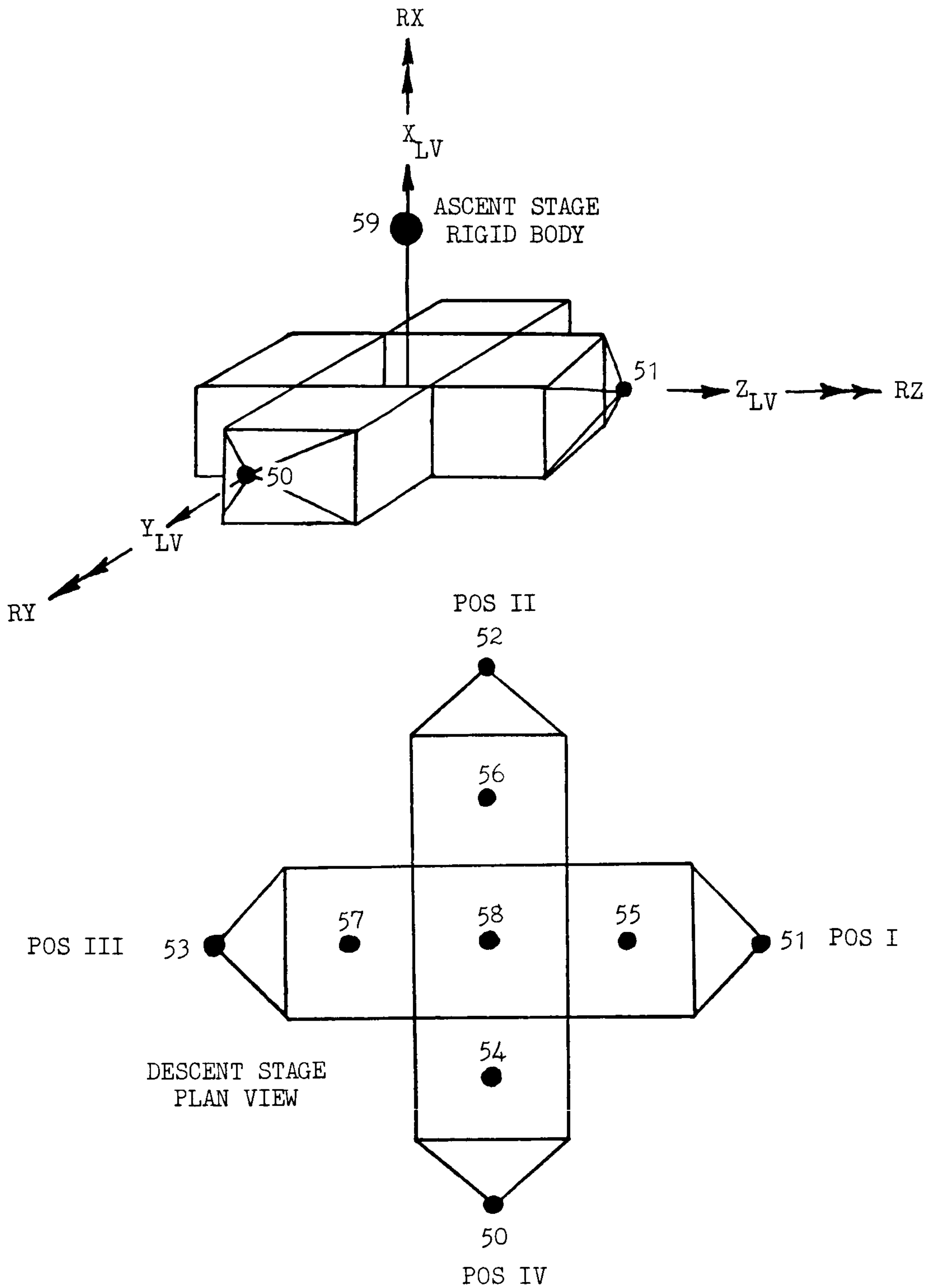
* Hurty, W. C. and Rubinstein, M. F., Dynamics of Structures, Prentice Hall, N. J., 1964.



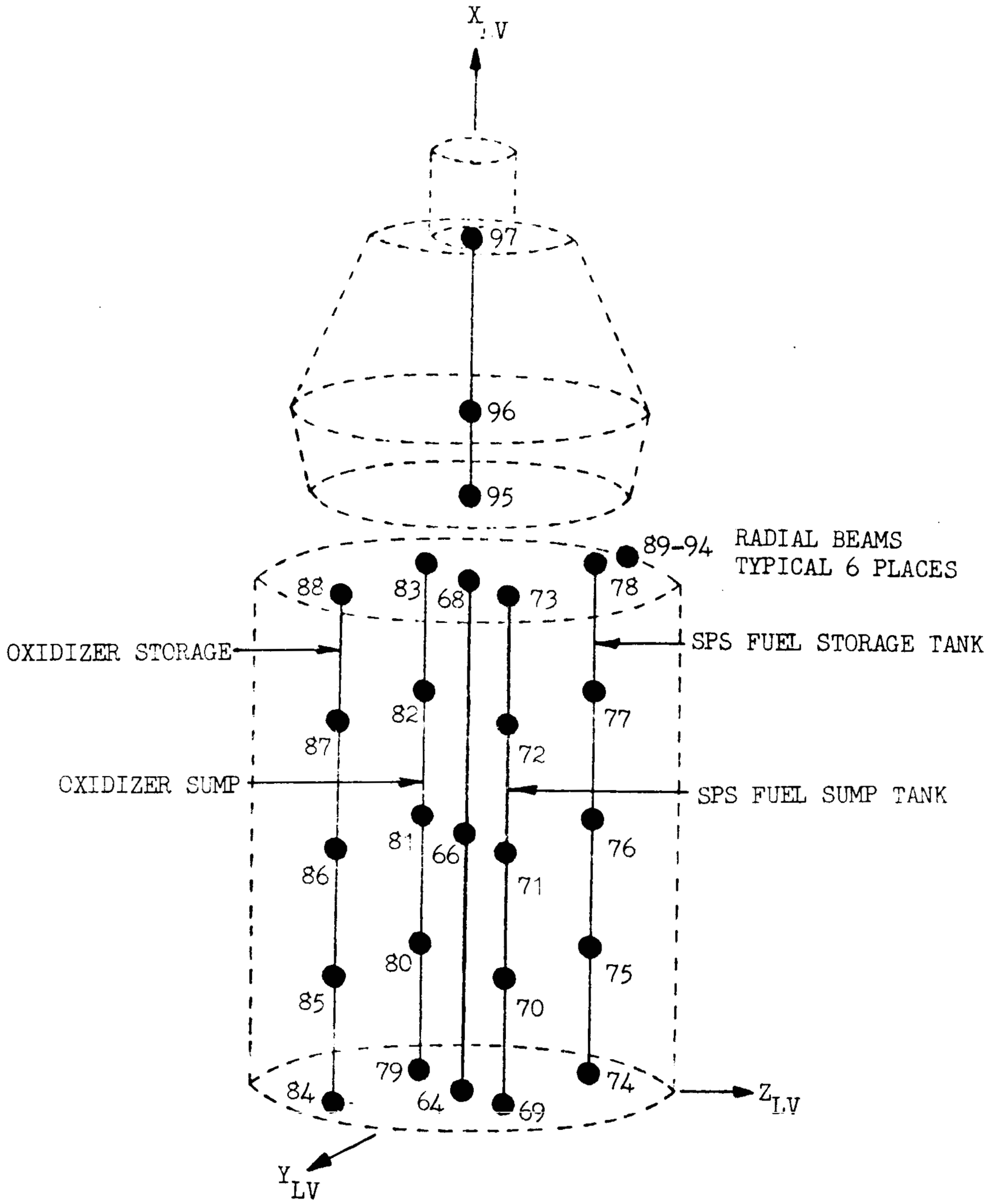
SLA/LM/IU/S-IVB FWD SKIRT/VATF MODEL

FIGURE 1



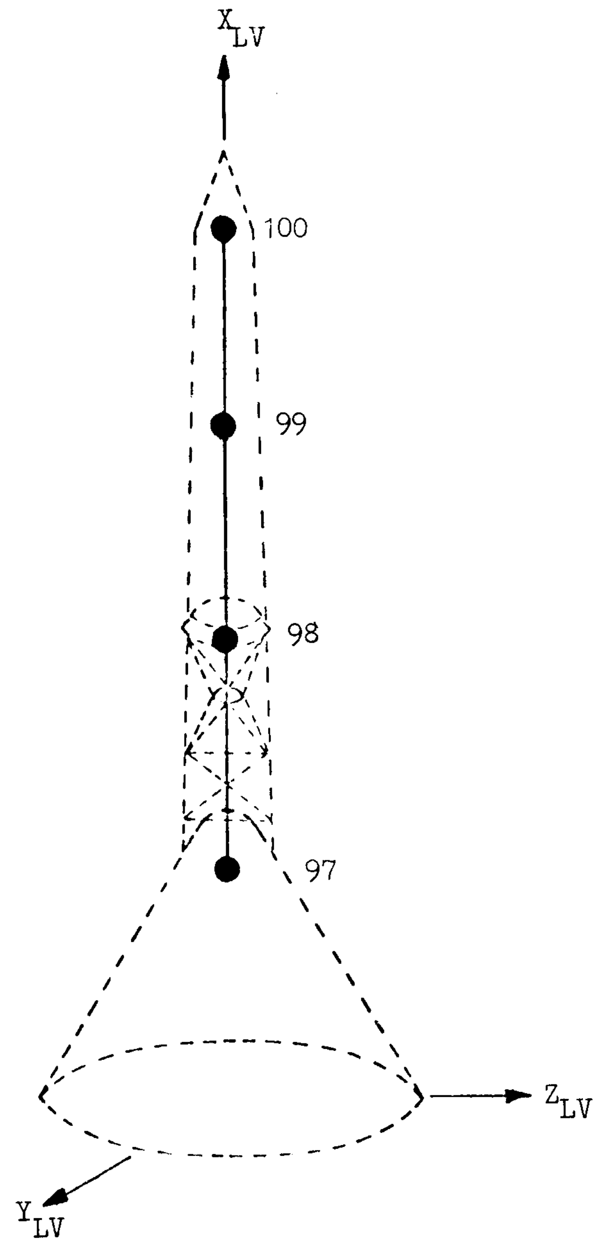
LM MODEL

FIGURE 2



CSM REDUCED-DETAILED MODEL

FIGURE 3



LES MODEL

FIGURE 4

REFERENCES

1. Comparison of Structural Model Analysis and Short Stack Dynamic Test, D2-118129-1, The Boeing Co., September 30, 1968.

2. MSFC TWX to MSC, Attention D. C. Wade, ES2 Subject Engine Oscillation Loads.

3. Spectrum Analysis of Apollo 4 and Apollo 6 Data, Memorandum For File, J. Z. Menard, October 25, 1968.

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From: R. E. Hunter

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